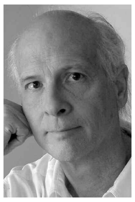
EMIN GÜN SIRER AND RIK FARROW

some lesser-known laws of computer science

Emin Gün Sirer is an associate professor of computer science at Cornell University. His recent research centers on self-organizing peer-to-peer systems and a new operating system for trustworthy computing.

egs@systems.cs.cornell.edu



Rik Farrow is Editor of *;login:*.

rik@usenix.org

Note: This work is based on a Four Minute Madness talk created by Emin Gün Sirer and presented during HotOS XI .

GORDON MOORE'S FAMOUS LAW [1], which successfully predicted an exponential increase in the complexity of integrated circuits, has had wide impact. It has not only captured the reasons behind the meteoric rise of computer science as a discipline, but it also predicted and shaped expectations for new processors. It has withstood the test of time and has become a household concept across the globe. We look at some other trends in computer architecture that have so far been ignored and provide extrapolations of where other trends might lead us in the decades to come.

Moore's Law

Gordon Moore was working for Intel when he came up with his eponymous law. Moore's Law is not a real law, in the sense of a universal and invariable fact about the physical world (the sense in which real scientists use the term), but it comes close in describing a phenomenon that has shaped the latter half of the 20th century. At the time Gordon Moore came up with his law, he was attempting to extrapolate the growth of component density that could be successfully manufactured using integrated circuit technology. In 1965, Moore wrote, "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year."

Five years later, the Caltech professor and VLSI pioneer Carver Mead actually started describing this brief statement as Moore's Law. Over time, Moore's Law evolved into the statement that the performance of computers doubles every 18 months. There are three remarkable things about this law. First, it was based on very scant data when it was first formulated. Gordon Moore was not afraid to make bold predictions based on facts as they were available to him. Second, the mere enunciation of the law affected the manufacturing standards to which new technologies were held, thus reinforcing the law itself. This suggests that the act of naming a law helps render it valid, or at least causes the world to bend slightly to accommodate the law, thus overlooking slight errors in extrapolation. Finally, any law that can last more than 40 years and carries its observer's name guarantees instant name recognition (not that Gordon Moore, a renowned computer architect and co-founder of Intel, would have needed it), which creates incentives for other computer scientists to replicate the feat by observing other trends.

It is not surprising, then, that many other "laws," similar in spirit to Moore's, have been proposed. For instance, it has been well known for quite some time that disk drive capacities tend to double every 18 months. In an article published in *Scientific American* in 2005, this observation was dubbed "Kryder's Law," after Mark Kryder, senior vice president and CTO of Seagate. For this deed, Kryder may achieve the same level of fame as Moore.

Other people have attempted this dual feat of devising a law that successfully matches the growth of some computer-related feature and becoming famous. Barry Hendy of Kodak Australia coined Hendy's Law, "The number of pixels per dollar found in digital cameras will double every year." Although a user named Barry.hendy has edited Wikipedia to insert Hendy's Law under the discussion for Moore's Law, it has so far failed to achieve the level of notoriety that Moore's Law has received.

Power Laws

Our quick look around at existing laws suggests that the low-hanging fruit has already been picked. But that is not to say that nameable observations have been exhausted. Careful examination of other trends in computer system architecture may indeed allow us to find new laws of exponential growth, especially if we, in the footsteps of Gordon Moore, allow ourselves to work from sparse and noisy data sets. In the rest of this article, we examine various trends in the hope of predicting the future of computer systems.

The first and most obvious trend is a tactile one that is taking place on or under every desktop. From around 1950, up until about 1995, computers had a single power button. Old-timers will fondly remember that "big red button" that promised to cut power (in an emergency) to mainframe computers. The very allure of such buttons led to their being enshrined in plexiglass cases lest an enthusiastic visitor be tempted to see if the button actually did something [2]. Most other computers, from minicomputers to workstations to early PCs, also came with a single power button, often located in the back next to the power cord.

Fast-forward to 1995, and you can see that PCs now have two power buttons, one on the back and one on the front. The Power Button Law thus presents itself: The number of power buttons doubles every 50 years. Although our data set is small, we can already see evidence that this trend is continuing: If you look just beneath the power button on most PCs, you can see a budding "proto-button" that, depending on the operating system and perhaps the phase of the moon, restarts the machine or does nothing. We are confident that it will slowly develop into a full-fledged power button over time (Figure 1).

FIGURE 1: A 1995 PC CASE (TOWER FORMAT), WITH PROTO-BUTTON APPEARING JUST BELOW THE FRONT PANEL POWER BUTTON

The observant reader will already have detected a problem with our first candidate for the Power Button Law: We may have to wait until 2045 until we have enough data points (or power buttons). Perhaps other candidates for power laws will be easier to assess.

Until 1990, PC-class machines did not make noise. Well, there was the familiar keyboard beep, along with other less consequential sources of noise (fans and hard drives). What changed around that time is that PCs started to include CD drives capable of playing music CDs. These CD drives had a single volume control, typically a hardware knob.

Fast-forward several years, and PCs running Windows have four means of controlling volume: the hardware volume control knob, the audio driver settings, the system-wide mixer setting, and the application-level volume setting. Linux and Mac OS are not far behind, either! This leads us to the Volume Control Law: The number of volume controls on a computer doubles every five years. Note that this law has a shorter period, and thus it will be quicker to verify. Still, the number of data points acquired so far is vanishingly small, leading us to continue our search for power laws.

It is well accepted among researchers that sensors are tiny computing platforms fundamentally limited in resources. For academicians, this has led to a tremendous boon: There has been much research targeting sensor platforms. Yet, despite the seemingly universal belief that sensor platforms will forever resemble 8-bit computers from 1983, actual sensors deployed in the field have been evolving rapidly. In Table 1, we summarize the salient features of several sensor platforms (from a period covering 1998 to 2002 [3]) to see whether we can observe any architectural trends.

	WeC 1998	**Dot 2000**	**Mica 2 2002**
CPU speed	~4 Mhz	~8 Mhz	~16 Mhz
Program memory	8 Kbytes	16 Kbytes	128 Kbytes
RAM	0.5 Kbytes	1 Kbyte	4 Kbytes
Power	45 mWatts	45 mWatts	75 mWatts
LEDs	~0	~1	~2

TABLE 1: SENSOR MOTE EVOLUTION, SHOWING A SLOW BUT STEADY INCREASE IN RESOURCES

Several interesting trends present themselves. First, we can see that the CPU speed doubles every ~2 years, roughly in step with Moore's Law (so sensors are not so static after all, and Gordon Moore beat us to the observation, yet again). Similarly, program memory as well as RAM doubles every ~1.5 years (this is a conservative estimate that does not account for the type of breakthrough flash memory might bring). And although our data on the number of LEDs is noisy, it appears that the number of pixels available on a sensor is doubling every ~2 years.

Based on these laws, we can extrapolate what sensor motes will be like in 2020 (12 years from now, plus 1 to be conservative):

- Mote CPUs run at 1 GHz.
- Motes have 32 MB program memory and 1 MB RAM.
- Motes house somewhere between 64 and 192 pixels, which would resemble a Christmas tree if they were to consist of LEDs, so are more likely arranged as a scrolling dot-matrix LCD display.

Pushing our extrapolation out a bit farther to 2050, sensor motes will, by then, have:

- 65-GHz CPUs
- 2 TB of program memory and 67 GB of RAM
- 1024x768 pixel displays
- 4 power buttons
- 2048 volume controls

Summary

Following power laws to their illogical but consistent conclusions produces ridiculous results. Thus, we now have a candidate for a lasting law: The obsequious following of power laws inevitably leads to impossible predictions.

REFERENCES

[1] Moore's Law: http://en.wikipedia.org/wiki/Moore%27s_law.

[2] Alex Papadimoulis, "The Big Red Button": http://worsethanfailure.com/Articles/The_Big_Red_Button.aspx.

[3] The family of motes: webs.cs.berkeley.edu/papers/hotchips-2004-mote-table.pdf.